Do Clean Cookstoves Reduce Biomass Fuel Consumption?

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Table of Contents

Abstract

Despite widespread global efforts to promote clean cookstoves, surprisingly little is known about whether they actually deliver reduced biomass fuel consumption when used in real-world settings. Using cross-sectional household survey data from Uttar Pradesh (UP) and Uttarakhand (UK) in India, we examine the impact of clean cookstoves on three key outcomes related to solid fuel consumption and stove use with OLS regression, propensity score matching, and the Heckman two-step estimator. Results from the Heckman two-step estimator suggest that using a clean cookstove is associated with daily reductions of 3.9 kg of biomass fuel, 83 fewer minutes cooking on traditional stoves, and 0.5 fewer hours collecting biomass fuels. Our results support the idea that efforts to promote clean stoves among poor rural households in India can lead to reductions in solid fuel use and time spent cooking on traditional stoves, and that any rebound effect towards greater amounts of cooking on multiple stoves, is not sufficient to eliminate these gains.

1. Introduction

Nearly 40% of the world's population relies on solid biomass fuel for cooking purposes (Bonjour and Adair-Rohani, 2013), while in India as much as 70% of the population cooks with biomass fuels (Census of India, 2011). Traditional cooking with solid fuels and inefficient stoves contributes to numerous health problems (Lim *et al.*, 2012), releases climate-warming greenhouse gases and black carbon emissions (Bond 2004; Ramanathan and Carmichael 2008), and exacerbates local air quality and other environmental problems. In particular, unsustainable harvesting of fuelwood for cooking can lead to forest degradation and local deforestation, especially in densely-populated areas (Chen *et al*., 2006; Heltberg, 2004; Geist and Lambin, 2002). Extraction is more likely to exceed regeneration in areas with low biomass production potential or where forest resources are already threatened by population pressure and patterns of land-use change (Bensch and Peters, 2013).

Clean cookstoves have the potential to address these negative impacts of traditional cooking if they allow more efficient combustion of biomass fuel, or use clean fuels, such as LPG. Such stoves would thereby reduce the amount of biomass fuel and smoke emissions from cooking. Partly because of these arguments, the UN Global Alliance for Clean Cookstoves has set an ambitious goal of getting 100 million households worldwide to adopt improved stoves (GACC, 2010). In India, where the study described in this paper took place, the National Biomass Cookstoves Initiative seeks to provide 160 million ICS to households currently using solid biomass fuel (Venkataraman *et al*., 2010). Yet surprisingly little is known about whether clean stoves actually deliver their purported benefits in health and fuel savings when used under real-world conditions. Empirical evidence of whether clean stoves deliver these supposed benefits is mixed. Not only is adoption of clean cookstoves constrained by barriers such as price, lack of awareness, and preferences for traditional stoves (Lewis and Pattanayak, 2012; Jeuland *et al*., 2013), but households often also maintain the use of "dirty" fuels and traditional stoves even after adopting clean stoves (Heltberg, 2004; Masera and Navia, 1997). Low rates of adoption and use, as well as stacking of stoves and fuels imply that adopting a clean stove may not reduce biomass fuel consumption or alleviate the adverse effects of traditional cooking as much as one would expect.

The analysis in this paper investigates this question using cross-sectional household survey data from Uttar Pradesh (UP) and Uttarakhand (UK) in India. We examine the impact of clean cookstoves on three key outcomes related to solid fuel consumption and stove use: 1) daily amount used and 2) time spent collecting biomass fuels, and 3) cooking time on traditional stoves. We hypothesize that owning and using a clean stove is negatively associated with each of these outcomes. To estimate the effect of clean cookstoves, we first use OLS models both with and without hamlet fixed effects. Because households that choose to purchase and use a clean cookstove may be systematically different from those that do not in ways that are not accounted for in the simple OLS model, these estimates may be biased. To address this selection problem, we next use propensity score matching to estimate the effect of clean cookstoves between observably similar households, and then compare these results with those obtained using a Heckman two-step estimator that aims to adjust for selection bias using a different approach.

The results of these analyses generally reveal a significant relationship between owning or using clean cook stoves and lower biomass fuel consumption, lower time spent cooking on traditional stoves, and reduced time spent collecting biomass fuels. Results from the Heckman two-step estimator suggest that using a clean cookstove is associated with daily reductions of 3.9 kg of biomass fuel, 83 fewer minutes cooking on traditional stoves, and 0.5 fewer hours collecting biomass fuels. The data also provide strong evidence of stove-stacking, even though this behavior does not offset the negative effect of using a clean stove on biomass fuel consumption and collection. Our results provide support to the idea that efforts to promote clean stoves among poor rural households in India can in fact lead to significant reductions in solid fuel use and time spent cooking on traditional stoves, and that any rebound effect towards greater amounts of cooking on multiple stoves, is not sufficient to eliminate these gains.

The paper is structured as follows. Section 2 discusses the literature on the impact of clean stoves and household demand for fuel. Section 3 describes the data, and the empirical specifications are presented in section 4. Results follow in Section 5, while Section 6 discusses and concludes.

2. Background on clean stove impacts and household fuel demand

The ultimate effect of adoption of cleaner stoves on biomass fuel consumption depends on how intensely households use clean stoves relative to traditional cookstoves, on the relative efficiencies of their different cooking options, and on the effect of having multiple stoves on cooking practices. Accordingly, empirical evidence concerning the impact of clean cookstoves on biomass fuel consumption is varied and inconclusive. Applying quasi-experimental methods, Adrianzen (2013) and Pattanayak *et al*. (2004) suggest that clean stoves and fuels are associated with lower biomass fuel use, while Nepal *et al*. (2010) finds that improved stoves had no effect on firewood consumption, and in some cases were even associated with greater firewood consumption. Experimental evidence is similarly mixed. In Orissa, India Hanna et al. (2012) find that improved stoves had no effect on biomass fuel consumption, while in Senegal, Bensch and Peters (2013) find that ICS owners in Senegal use significantly less firewood per week than non-owners.

To better interpret this evidence, it is important to account for households' potential behavioral adjustments following acquisition of a clean stove. Because many rural households in the developing world do not purchase biomass fuels, but rather collect them freely from local forests and commons, we draw on the household production framework to account for the linkage between household consumption and production decisions related to fuel collection and cooking (Chen *et al*., 2006; Heltberg *et al*., 2000; Heltberg, 2005; Heltberg, 2004; Pattanayak *et al*., 2004; Edwards and Langpap, 2005). In this model, households are assumed to maximize utility generated by consumption of fuel services (cooking and heating), other goods, and leisure, which are each subject to corresponding production functions and budget constraints. Household production of fuel services depends on the quantity and types of stoves and fuels used. Quantities and types of fuels used are determined by preferences, household budget constraints, and prices. For biomass fuels that are collected rather than purchased, the relevant prices are shadow prices, which are determined by the opportunity cost of fuel collection (Pattanayak *et al*., 2004).

The household production model points to a set of economic, demographic and social factors that should be considered when analyzing the determinants of stove and fuel choice and consumption, and which perhaps help to explain the inconclusive findings in the prior empirical literature (Pattanayak *et al*., 2004; Pattanayak and Pfaff, 2009; Edwards and Langpap, 2005; Masera *et al*., 2000). Factors that affect a household's opportunity cost of biomass fuel collection – e.g. income, education, distance to biomass sources of fuel, or terrain and local forest quality variables – affect relative costs of different fuels (Heltberg, *et al*., 2000; Pattanayak *et al*., 2004). Besides the prices and shadow prices for fuels, income and access to credit influence households' ability to finance the purchase of clean stoves and fuels. Additionally, because modern stoves and fuels are sometimes viewed as status symbols, perceived relative wealth may be a more important determinant of fuel-switching than actual income (Masera *et al*., 2000). More educated households or female headed households may be more conscious of the harms of traditional cooking or more aware of the benefits of clean stoves or fuels, and therefore more inclined to switch to these (Jeuland and Pattanayak, 2012; Pachauri and Rao, 2013). Meanwhile, household demographic factors may also affect the demand for fuel. For example, larger households have greater cooking needs but also benefit from economies of scale in cooking. In a systematic review of 32 studies, adoption of clean stoves was found to be positively associated with income, education, and access to credit, and negatively associated with social marginalization (Lewis and Pattanayak, 2012).

Less routinely considered in the empirical literature on stove and fuel use decisions is the role of psycho-social factors such as time preferences and risk aversion. Risk aversion may be important given that the benefits of using clean cookstoves may be highly uncertain for households (Jeuland and Pattanayak, 2012; Mobarak and Miller, 2011). Likewise, to the extent that different households place more or less emphasis on long-term benefits relative to upfront costs of adoption or behavior change, time preferences can provide clues on who will adopt. For the same reasons, households may delay use of cleaner stoves and fuels because these require learning, which could perpetuate a self-reinforcing cycle of non-use that leads to no or low benefits.

Intuitively, one might expect that overall solid fuel use would decrease with adoption of cleaner cooking technologies, but this need not be the case. Switching to cleaner burning fuels or stoves is often treated in the literature as a move up the "energy ladder;" as income and access to technological solutions increase, households are able to climb onto higher rungs of this ladder. But empirical evidence finds that households continue to use traditional stoves and fuels, even after adopting cleaner technology (Edwards and Langpap, 2005; Masera *et al*., 2000). More efficient stoves effectively decrease the price of fuel resulting in both income and substitution effects that affect the demand for biomass fuel in opposing ways (Sorrell *et al*., 2009; Greening *et al*., 2000; Nepal *et al*., 2010). Thus, the net effect on household biomass fuel consumption is unclear, especially when households engage in stove stacking or if the marginal opportunity cost of fuel collection is low. In fact, if households that own both clean and traditional stoves substitute towards traditional stoves for more fuel-intensive cooking – biomass fuel consumption may actually increase (Nansaior *et al.*, 2011; Masera *et al*., 2000; Heltberg,2004; Ruiz-Mercado *et al.*, 2011).

In addition, households may choose to maintain use of stoves relying on different fuels for a variety of economic, social and cultural reasons as well as constraints on fuel availability, such that gains from improved stoves become muted (Masera *et al*., 2000). For example, using multiple stoves and fuels may serve as an insurance policy when one type of fuel is scarce or unreliably supplied. Different cookstoves or fuels may also be better suited to specific cooking tasks, such that these technologies are imperfect substitutes (Masera *et al*., 2000; Edwards and Langpap, 2005). Households may prefer the taste of certain foods when these are cooked on biomass stoves (Smith *et al.*, 2011; Heltberg, 2005; Ruiz-Mercado *et al.*, 2013; Alem and Hassen, 2013).

It should also be noted that empirical studies of the effect of clean stove adoption on household solid fuel consumption are complicated by the likely differences between households that own and use such clean stoves and those that do not. Using data from China, Mueller *et al.*

(2013) demonstrate that such differences may be correlated with the key outcomes that stove impacts studies measure, which can bias the estimated impact of ICS. Selection may be driven by many observable and unobservable factors such as income, price of fuel, opportunity cost of collecting fuel, patience, risk-taking behavior, frugality and degree of care and concern for the local community and resources that impact both the decision to purchase a clean stove and fuel consumption (Mueller *et al.*, 2013).

3. Data and Description

We utilize data from a household survey of 2,120 households conducted in Uttar Pradesh (UP; N=1,057) and Uttarakhand (UK; N=1,063) in India during June-August 2012 (summer and early monsoon season). The survey data includes information on a wide range of household socioeconomic and demographic characteristics, perceptions about stoves and fuels, household cooking practices, stove ownership and fuel use, and time and risk preferences, all of which are emphasized in the literature discussed above. In the section on cooking practices, the survey contains data on whether households owned one of 11 types of stoves, how many burners these had, whether the stoves had been used in the past week, how often the stove is typically used, and how long the stove is used on a typical day. Similarly, the baseline survey gathered data on whether households use each of 9 fuel types, how regularly they use the fuel, how much money they spend on the fuel per month, how much time is spent collecting the fuel, and what quantity of each fuel is used. All of these data are self-reported.

Shortly after the full household survey, a 24-hour fuel measurement survey was also conducted in a randomly selected sub-sample of 1,234 households of these original households (UK=460; UP=774 households). The fuel measurement survey contains information about household's cooking practices and stove and fuel use during a monitored 24-hour period. Initial quantities of biomass fuels were weighed. Enumerators returned the following day to survey the households and weighed the remaining amount of fuel. The fuel measurement questionnaire includes questions on which meals households cooked, the number of household members for whom food was prepared, whether the household cooked the same number of meals as usual, how much time each stove the household owns was used for cooking and heating, and which fuels were used, all during the monitoring period. Data on fuel consumption from the fuel measurement survey provides an alternative account of how much fuel households use, and a greater ability to control for a variety of factors that might be confounders of fuel and cooking time outcomes. This data may be less subject to self-report bias, but is more difficult and time-consuming to collect and may also not be fully representative of average use.

Table 1 Panel A presents descriptive statistics for household stove and fuel use. Approximately 22% of households own some kind of clean stove, most of which are LPG stoves.[1] Households report using approximately 9 kg of biomass fuel per day, which includes firewood, crop residues, leaves, twigs, and dung cakes. There is substantial variation in fuel use by state. In UP, households use an average of 11.5 kg of biomass fuel per day, which is almost twice as much as households in UK use during this season. Data from the fuel measurement survey corroborates the sample average of 9 kg of biomass fuel per day, however in UK the

[1] Ninety-four percent of the clean stove owners have an LPG stove, with the remaining 6% comprised of kerosene stoves, electric stoves, and biogas stoves. Only 4 households reported owning any kind of commercially marketed ICS.

weighed amount of fuel used is slightly larger than what was reported in the full household survey, while in UP the amount weighed is slightly smaller. Households report spending on average more than 3 hours (189 minutes) per day cooking on traditional stoves, with households in UK reporting an average almost as high as 5 hours per day, while in UP the reported average is approximately 1.5 hours per day. Data from the fuel measurement survey largely confirms the average cooking time for the entire sample, with a lower cooking time reported for UK and a higher reported cooking time in UP. On average, households spend approximately 2.2 hours per day collecting biomass fuels, with households in UP spending more time. On average, households report the market price for a quintal (100kg) of firewood to be 523 rupees (USD \$9.50[2]), but only 32% of the sample reports spending any money on firewood. The reported price for LPG cylinders reflects government subsidies for LPG, in particular for below poverty line (BPL) households. On average, households own more than one stove and use more than one kind of fuel. Clean stove-owning households spend less than 30 minutes per day cooking with these non-traditional stoves (or 9% of total reported cooking time), and therefore continue to rely heavily on traditional technologies. Figure 1 presents biomass fuel consumption, time spent cooking on traditional stoves, and time spent collecting biomass fuels broken out by clean stove ownership and state.

Table 1 Panel B presents descriptive statistics for household demographic and socioeconomic characteristics. The sample is predominantly Hindu, with a larger proportion of non-Hindus residing in UP. On average, 26% of households are in officially designated scheduled castes or tribes, traditionally disadvantaged populations within India. Households have approximately 5 members and 18% of households are headed by women, and in UK there are substantially more female-headed households. On average, both household heads and primary cooks have little education. In UP, primary cooks have less than three years of education, while in UK they average almost 5 years of education. Households have total expenditures of approximately Rs. 5,800 per month (approximately USD \$105), and 67% report being below the official poverty line. In the full sample, households average 10 hours of electricity per day, but the UK average is 17 hours per day, while in UP households have only three hours of electricity per day. Only 14% of households have ever taken out a loan, saving is possible for only 15% and only 13% of households participate in self-help groups (SHG).

4. Empirical Specifications

The empirical analyses presented in this paper examine the impact of clean cookstoves on three outcomes: 1) amount of biomass fuel consumption; 2) time spent cooking on traditional stoves; and 3) time spent collecting biomass fuels. We first consider these impacts using ordinary least squares regression (OLS). In these estimations, we control for a rich set of household level characteristics obtained from the survey that are highlighted in the previous literature on stove and fuel use, and that could therefore confound the measurement of impact. Even so, households that own clean stoves may remain different (in terms of unobservable characteristics) from those that do not; in addition the method of statistical control may be imperfect if there is little overlap between clean stove owners and non-owners. To address these issues, we next employ matching methods based on the propensity to own a clean stove as a function of a set of observable

[2] During the summer of 2012, when the baseline survey was conducted, USD \$1 = 55 Rs.

household characteristics. Finally, to address systematic differences across clean stove owners and non-owners, we also employ a Heckman two-step estimator that adjusts for selection bias.

4.1. OLS Regression

We estimate the following regression:

$$Y_{ij} = \beta_0 + \beta_1 S_{ij} + \theta X_{ij} + \gamma_j + \varepsilon_{ij} \tag{1}$$

The dependent variable Y_{ij} represents one of the three outcomes of interest for household i in community j and S_{ij} is an indicator variable for whether the household owns a clean stove. Because households may be stacking stoves and not regularly using their clean stoves, we estimate these models with S_{ij} representing a binary indicator for both ownership and use of a clean stove in the past week. X_{ij} is a vector of household level characteristics that impact these outcomes. These include household size, which affects both demand and supply of biomass fuel, and a squared term for household size, which addresses potential nonlinearities and economies of scale in the effect of household size on each outcome. They also include factors that affect the opportunity costs of biomass fuel collection and household preferences for clean fuels and stoves: an indicator variable for UP, years of education of the household head, years of education of the primary cook, the number of children under 5 in the household, and an indicator for female-headed household. To incorporate factors related to the budget constraint and income, we use logged average monthly household expenditures, an indicator for the household reporting a higher than average price of firewood, the reported market price of LPG cylinders, hours of electricity, an indicator for access to credit, and, an indicator for household involvement in a self-help group (SHG). The term γ_j represents a hamlet (community) fixed effect, which controls for unobserved factors that may impact fuel consumption of all households within a particular community (e.g., quality of local forests), but that vary across hamlets, and ε_{ij} is a random error term, adjusted for correlation of observations at the hamlet level. We estimate these regressions primarily using the full household survey-based measures of outcomes, but also repeat them for the subset of households for which we conducted 24-hour fuel measurements.

4.2. Propensity Score Matching

We next use propensity score matching to compare households that own clean stoves to observably similar households that do not own clean stoves. In the first stage, we model clean stove ownership to be a function of household characteristics using probit regression:

$$S_{ij} = \alpha + \theta X_{ij} + \varepsilon_{ij} \tag{2}$$

The dependent variable S_{ij} again represents a binary indicator for both ownership and use of a clean stove in the past week, X_{ij} represents a vector of household characteristics for household i and ε_{ij} is a random error term adjusted for correlation of observations at the community level. The vector X_{ij} includes household characteristics such as household size, education of primary cook and head of household, awareness of and belief that clean stoves and fuels can mitigate the negative effects of traditional cooking, an indicator variable for female headed households, average price of LPG, access to credit, participation in self-help groups, several proxies for income (e.g., number of rooms in the house, perceived relative wealth and logged expenditures), and variables that reflect risk avoidance (e.g., risk preference and ownership of toilets). We then use this model to generate predicted probabilities first of clean stove ownership (and second of clean stove use in the past week), for matching owning and non-owning households based on their propensity to own (or use) a clean stove. Finally, we compare the mean difference in biomass fuel consumption, cooking time on traditional stoves and time spent collecting biomass fuels across these two matched samples.

Results from this first stage are presented in Table 2, and balance tests showing normalized differences for the unmatched and matched samples are shown in Table 3. Among other things, the results suggest that there is positive selection into clean stove ownership and use: proxies for income, years of education, age of the head of household, number of children under 5, female headed households, a belief that clean stoves and fuels can mitigate the negative effects of traditional stoves, and toilet ownership all have a positive and significant association with owning and using clean cookstoves. Household size, reported price of LPG, and lower risk aversion have a significant and negative association with owning and using clean stoves. Prior to matching, there are large imbalances in observables between clean stove owners and non-owners. PSM is largely successful in eliminating these differences, though normalized differences on a few variables (e.g. ownership of traditional stoves, perceived relative wealth and number of cellphones owned) remain somewhat large.

4.3. Heckman Two-step Estimator

Despite improving sample balance on the characteristics shown in Table 3, propensity score matching does not rule out the possibility that systematic differences in household characteristics between owners and non-owners of clean stoves that are not included in the matching algorithm, including variables not observed in the household data, might affect outcomes and bias estimates of the impact of clean stoves. As a robustness check, we also estimate the effect of clean stoves using an Heckman two-step estimator, which allows for correlation between unobserved factors that affect both the treatment (propensity to own and use clean stoves), and those that affect outcomes (Heckman 1976; Heckman 1979; Maddala 1983). The Heckman two-step estimator model is written as:

$$S_{ij} = \begin{cases} 1, & if\ \theta X_{ij} + \mu_{ij} > 0 \\ 0, & otherwise \end{cases} \tag{3}$$

$$Y_{ij} = \beta_0 + \beta_1 S_{ij} + \theta X_{ij} + \delta\lambda_{ij} + \varepsilon_{ij} \tag{4}$$

In the first stage, selection into the treatment S_{ij}, is modeled as a function of observable characteristics, X_{ij}. We utilize the same set of characteristics for the first stage as those used in equation 2, and model the probability of clean stove ownership using probit regression. Results from this first stage are presented in Table 2. In the second stage, each outcome Y_{ij} is modeled as a function of the treatment, the other independent variables, and the inverse Mills ratio (λ_{ij}), which is the ratio of the probability density function normalized by the cumulative distribution function. The inclusion of the inverse Mills ratio in Equation 4 helps to correct for the non-random selection into clean stove ownership.

5. Results

5.1. OLS Regression Results

Table 4 presents the results for OLS regressions for the three outcomes of interest – biomass fuel consumption, time spent cooking on traditional stoves, and time spent collecting biomass fuels – for using a clean stove. The results for owning a clean stove were similar, although estimates for cooking time on traditional stoves are slightly smaller for clean stove ownership, and are not presented. Columns 1, 3 and 5 present results without hamlet fixed effects. Using a clean stove is associated with 2.2 kg less biomass fuel consumption per day, 89 fewer minutes cooking on traditional stoves and 0.5 fewer hours collecting biomass fuels per day. For all three outcomes the coefficient on clean stove use is negative and significant at the 1% level. When hamlet fixed effects are added to the model (Columns 2, 4 and 6), the point estimates for the effect of clean stove use on biomass fuel consumption and cooking time decrease somewhat, while the estimate for collection time remains the same; none of these estimates are significantly different from the coefficients obtained when these fixed effects are omitted, however. Accounting for hamlet fixed effects, using a clean stove is associated with a 22% reduction in the amount of biomass fuel used per day, 38% decrease in the time spent cooking on traditional stoves, and a 23% reduction in the hours spent collecting biomass fuels per day. These results suggest that clean stoves do not generally replace traditional stoves, but only reduce households' traditional stove use.

Turning to the other covariates included in Table 4, Household size has a positive effect on cooking time and a marginally positive effect on biomass fuel consumption, but no effect on collection time. For time spent cooking on traditional stoves, the negative and significant squared term on household size also suggests there may be economies of scale to cooking in larger households. The coefficients on the indicator for households living in UP are large and highly significant in all models, but also sensitive to the inclusion of hamlet fixed effects (which suggests that some of the systematic variation across states can be explained by community level differences). State-level differences are explored in more detail in Appendix Table A1, where the same OLS models are estimated separately for the sample living in each state. The results from these state-specific models suggest that using a clean stove is associated with much greater reductions in biomass fuel consumption and collection time in UP than in UK (however the biomass consumption estimates are more precisely estimated for UK), but much greater reductions in cooking time in UK than UP; these differences are statistically significant. Households in UP consume more biomass fuel (Table 1) than in UK, which suggests that fuel savings from using a clean stove are perhaps increasing in baseline fuel consumption. With estimates from the hamlet fixed effects model, using a clean stove is associated with a 36% reduction in biomass fuel consumed in UP, but only a 17% reduction in UK. Differences in time spent collecting biomass fuels may also be driven by baseline differences and households in UP on average spend more time collecting biomass fuels. This is likely due to differences in geographic location, forest quality and terrain. In UK, sample communities are located in the foothills of the Himalayan mountain range, which contains approximately 50% of India's forest cover (Malik *et al*., 2014), and thus households likely have greater access to forest resources than in the plains of UP. Household size has no impact in the regressions for UP, thus households in UK drive the effects seen in the full sample.

Returning to the results in Table 4, the education variables are mostly insignificant (except in column 6 for primary cook) in explaining differences in outcomes shown in Table 4, and coefficients are modest in size, suggesting that their effects on reliance on traditional stoves and fuels are minor. Female-headed households and households with more children under the age of 5 do spend more time cooking on traditional stoves, even as they report spending less time collecting fuel (though these effects are not all statistically significant when hamlet fixed effects are included). This may reflect a tighter budget constraint on time spent outside the home for such households. Though the individual variables reflecting socio-economic status (e.g., monthly expenditures, electricity and access to credit) are not consistently related to fuel use/collection time and time spent cooking, collectively they are positively related to these outcomes. Thus, even though improved stove ownership is somewhat positively related to income (as shown in Table 3), traditional stove and fuel use do not appear to be inferior goods among sample households. This provides further evidence on the importance of stove stacking among these households.

Somewhat unexpectedly, households that report higher market prices for firewood appear to consume more biomass fuel than those reporting low prices (the coefficients for the other outcomes have similar signs but are not statistically significant). This may however reflect the fact that most households in the sample do not purchase fuelwood, but collect it freely from the commons, such that higher perceived prices for this fuel simply reflect a greater propensity to collect more fuel. The coefficients for the effect of reported LPG price are only significantly (negatively) related to time spent collecting solid fuels in the model without hamlet fixed effects, and the estimates are noisy and inconsistent across outcomes. The price of LPG may not be widely known among non-LPG stove owners.

5.2. Propensity Score Matching Results

The results for the impact of using a clean stove on each outcome for the samples created by applying PSM are presented in Table 5. In model 1, using a clean stove is associated with 2.2 kg less biomass fuel consumption per day, 107 fewer minutes cooking on traditional stoves, and 0.7 fewer hours collecting biomass fuels. The results for owning a clean stove, which are not presented here, are generally similar but have smaller and less significant (in the case of biomass fuel consumption) point estimates. The PSM estimates are similar to both sets of OLS results; however, the point estimates for the effect on time spent collecting biomass fuels and cooking time with traditional stoves are larger. The difference for cooking time is significantly different larger than the OLS estimates, which suggests that owners of clean stoves differ from non-owners in attributes that affect their cooking needs beyond simply which type of stove is owned.

5.3. Heckman Two-step Estimator Results

Table 6 presents the regression results for the second stage Heckman two-step estimator for the three outcomes of interest. Using a clean stove is associated with daily reductions of 3.9 kg of biomass fuel, 83 fewer minutes cooking on traditional stoves, and 0.5 fewer hours collecting biomass fuels. The point estimate for the effect of using a clean stove on biomass fuel consumption is larger than those obtained using OLS or PSM, which suggests the possibility that those results may be biased downwards by failure to account for selection into owning a clean stove. On the other hand, point estimates for time spent cooking with traditional stoves and collecting biomass fuels are very similar to the OLS results, although the estimate for collection time is only significant at the 10% level. The effect on time spent collecting traditional fuels is notably similar across all three methods. Results for owning a clean stove, which are not presented here, demonstrate the same effects but with slightly smaller coefficients on owning a clean stove for all three outcomes. The larger estimates for using a clean stove suggest that not all improved stove owners use these consistently, such that the gains in fuel reductions and time spent cooking on traditional stoves are dampened. The point estimates for the effect of covariates included in the Heckman model are generally similar to those in the OLS model in terms of sign, magnitude, and significance.

Figure 2 presents the regression coefficients and 95% confidence intervals for the effect of using a clean stove on all three outcomes for each of the OLS, PSM and Heckman two-step estimator models. None of the estimates are statistically different from each other, as all of the confidence intervals overlap, and only for time spent collecting biomass fuels is the estimate not statistically different from zero using a 95% confidence interval in the Heckman model.

5.4. Sensitivity analysis using 24-hour fuel measurements

Finally, we investigate whether results change with use of the potentially more objective measures of fuel use and cooking time from the 24-hour monitoring of a subset of households described in Section 3. OLS regressions estimating the effect of using a clean stove during the monitoring period using these alternative measures are presented in Table 7. Using a clean stove during the monitoring period is associated with 3.8 kg less biomass fuel consumption and 113 fewer minutes cooking on traditional stoves, both of which are significant at the 1% level. Models that include hamlet fixed effects demonstrate a similar but moderately attenuated effect for use of a clean stove, but are nonetheless larger than OLS estimates from the full household survey. Overall, these estimates confirm the results from self-reported data in the household survey but are larger, suggesting that recall bias and measurement error bias downwardly bias the estimates from the household survey.

The results also show that the number of household members for whom food was prepared during the monitoring period is associated with somewhat greater amounts of biomass fuel used and cooking time. Cooking a midday meal is associated with more biomass fuel consumption and time spent cooking on traditional stoves, which suggests that this meal may be the larger than others, and that it is more likely to be prepared on a traditional stove. Preparing dinner is associated with 28 more minutes cooking on traditional stoves, but has no significant effect on the amount of biomass fuel consumed. This could be the result of households re-heating lunch and baking bread for dinner rather than preparing an entirely fresh meal. Preparing only food during the monitoring period is associated with significant reductions in biomass fuel consumption and cooking time on traditional stoves, relative to households that also prepared animal fodder or used stoves for heating purposes. Although significant for both biomass fuel consumption and cooking time, the effect is not statistically different from zero once hamlet fixed effects are included, suggesting that the need for heat or cooking animal fodder may be consistent within communities.

As an additional sensitivity test, we implemented propensity score matching and the Heckman two-step estimator using the 24-hour fuel measurements. With both methods, results using the fuel measurement data, which are not presented here, demonstrate that using a clean stove has a negative and statistically significant on weighed biomass fuel consumption and cooking time with traditional stoves. These magnitudes of the point estimates are largely similar across all methods and confirm the findings from both the OLS regressions using the same data and the PSM and Heckman estimates with the full household survey.

6. Discussion and conclusion

Many of the purported environmental and livelihoods benefits of clean cookstoves stem from the fact that these allow for more efficient cooking and reduce fuel consumption. Yet empirical evidence of the impact of these stoves on biomass fuel consumption remains surprisingly limited and inconclusive. Indeed, much empirical research has found evidence of stove-stacking, whereby households continue significant use of “dirty”, traditional stoves even after adopting cleaner technologies. Given this behavioral response to clean stoves, owning a clean stove may not actually result in consistently reduced consumption of biomass fuel.

In this paper we evaluated the effect of clean stoves on three key outcomes related to use of traditional stoves and fuels – amount of biomass fuel consumption, time spent cooking on traditional stoves, and time spent collecting biomass fuels – by households living in rural communities in two states of northern India, Uttar Pradesh and Uttarakhand. We first estimated impacts using OLS regression, before implementing two alternative estimation strategies that attempt to account for differential selection by households into clean stove ownership: propensity score matching, and Heckman’s two-step estimation procedure.

We found that clean cookstoves are consistently and generally significantly associated with reductions in biomass fuel consumption, time spent cooking on traditional stoves, and time spent collecting biomass fuels. In the Heckman two-step estimator, our preferred model, using a clean cookstove was found to be responsible for 3.9 kg lower biomass fuel per day, 83 fewer minutes cooking on traditional stoves, and 0.5 fewer hours collecting biomass fuels. The most striking differences across modeling approaches were observed for the time spent cooking with traditional stoves, which ranged from 72 minutes in the OLS model with hamlet fixed effects to 107 minutes in the PSM model. The larger Heckman estimates for biomass fuel suggest that OLS and PSM estimates may be downwardly biased by unobservable characteristics driving selection into stove ownership. This bias is potentially important given that it would imply considerably greater fuel and time-savings for households using clean stoves than is typically found in analyses relying on cross sectional data. It also suggests a need for additional longitudinal and/or experimental studies of the effects of clean stoves, given that we are not able to fully account for selection and endogeneity bias with the methods employed in this analysis.

Results investigating the effect of clean stove ownership as the main explanatory variable of interest were largely consistent with those for use, though coefficient estimates for use were surprisingly not always larger than those for ownership. The effect of clean stoves also appears to vary substantially by state, although results remain consistent and negative for clean stove-using households living in both locations. An additional contribution of this paper was incorporation of more objective or potentially less biased measures of fuel consumption and time spent cooking from a fuel measurement survey conducted in a sub-sample of the household survey. Our estimates of the effects of clean stove use based on these alternative measures were generally consistent with those from self-reports. In addition, including covariates that controlled for the type of meal prepared, whether households prepared only food, and the number of household members for whom food was prepared during a 24-hour monitoring period vastly increased the explanatory power of regression models. These results also revealed that some meals are more fuel intensive than others, which could lead to stove promotion efforts that are better targeted to changing specific fuel-intensive cooking behaviors. Further efforts to collect detailed, objective data on stove and fuel use per cooking activity appear warranted to better understand these complexities.

Our findings are consistent with a number of papers in the literature that find significant reductions in biomass fuel consumption from clean stove use (Berrueta *et al*., 2008; Bailis *et al*., 2007; Edwards and Langpap, 2005; Pattanayak *et al*., 2004; Adrianzen, 2013). An important difference in our study however, is that the majority of clean stove users in our sample owned an LPG stove, rather than an improved biomass-burning stove. In fact, previous studies on the effects of non-biomass improved stoves have been surprisingly inconclusive, raising questions about the extent to which such stoves are used by often cash-constrained, rural households (Nepal *et al.,* 2010). Nonetheless, our results provide further evidence on the importance and prevalence of stove-stacking behavior, since even households that used clean stoves regularly maintained substantial use of traditional stoves. In our sample, this stacking did not negate the effect of using a clean stove on time and fuel savings, but it does have implications for other impacts that rely on greater reductions in traditional stove use (e.g. reduced exposure to dangerous emissions).

Overall, however, our results show that households that own clean stoves are typically using them, which is an important finding given the global efforts to distribute clean cookstoves. These endeavors stem from concern over the deleterious effects of household air pollution (HAP) on health, as well as the impact of traditional cooking on deforestation and emission of greenhouse gases. Forest quality and the global climate constitute public goods, which suggests that clean cookstoves, provided they actual deliver reduced biomass fuel consumption and emissions, may be candidates for subsidies. For policymakers trying to promote clean cookstoves to address these issues in India, our results have several policy implications. First, it is important to encourage not only greater adoption of clean cookstoves but also incentivize use and discourage stacking, since larger effects were found for stove use than simply ownership in all models. Although reported prices of LPG cylinders were insignificant in almost all modes, LPG prices were significant determinants of adopting clean stoves in the probit models of clean stove ownership and use. This pattern of results may reflect that LPG prices affect biomass fuel consumption only through their effect on the initial decision to purchase an LPG stove and do not have an independent effect on fuel consumption (Edwards and Langpap, 2005). Therefore policymakers aiming to increase adoption of clean stoves might consider larger subsidies of LPG and other clean fuels to help incentivize adoption.

Second, our results show that more educated households and households that believe their use of cleaner fuels can have a positive impact on the negative effects of traditional cooking are more likely to own and use clean cookstoves. On the other hand, income (proxied by average household expenditures) had no effect on ownership of clean stoves and very minimal effects on final outcomes in only a few models, which supports notions of a nonlinear energy ladder because even wealthier households maintain use of biomass fuels. These results suggest that stove dissemination programs should have a large education and awareness-building component and not focus on prices alone.

Finally, results from the fuel measurement survey demonstrate that households prefer different stoves for different meals and cooking activities, which has several implications. First, if clean cookstoves are not well-suited to particular foods or meals, neither subsidies nor education campaigns will be sufficient to induce households to use clean stoves for those purposes. If households prefer to use traditional stoves for the most time or fuel intensive activities, such as preparing bread, then these estimates may represent an upper bound for the effects adopting an LPG stove. Second, efforts to promote improved stoves should be sensitive to cultural preferences for food and the appropriateness of clean stove technologies for satisfying these preferences. Clean stoves that are better aligned with household needs are more likely to be used and thus will have greater potential to reduce biomass fuel consumption.

Although we find very similar results for ownership and use of clean stoves, our results point to extensive stove-stacking behavior. While our results do not suggest that stove-stacking offsets the fuel reductions from using a clean stove, clean stove owners predominantly have LPG stoves and this may not be the case for households using improved biomass burning stoves. Thus, more research is needed on how to reduce stove-stacking with traditional stoves. Part of this can be addressed through stove design, as discussed above. But also a better understanding of what impedes households from making a complete switch to a clean stove is needed. Do supply side issues, such as cost and reliability of clean fuels or lack of locally available maintenance and repair, dominate? Alternatively, there may be demand side barriers such as lack of knowledge on how to properly use, clean and maintain stoves. More research on these issues will help close the gap on how to encourage both greater adoption and use of clean stoves and thus achieve the benefits that clean cookstoves promise.

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Table 1. Stove, fuel use and household characteristics

	Full Sample			UK			UP		
	N	Mean	SD	N	Mean	SD	N	Mean	SD
Panel A: Household stove and fuel use									
% Own clean stove	2071	22%	41%	1036	31%	46%	1035	12%	33%
% Used clean stove (past week)	2069	20%	40%	1036	30%	46%	1033	11%	31%
Total biomass fuel (kg/day)	2120	9.0	11.3	1063	6.6	6.3	1057	11.5	14.3
Total biomass fuel used during monitoring period (kg)	1234	9.0	4.8	460	8.6	5.5	774	9.1	4.3
Cooking time on traditional stoves (minutes/day)	2120	189.2	153.8	1063	287.4	136.6	1057	90.3	96.0
Cooking time on traditional stoves during monitoring period (minutes)	1234	199.8	96.1	460	222.6	127.7	774	186.2	67.3
Hours collecting traditional fuels	2120	2.2	2.0	1063	1.8	1.6	1057	2.5	2.3
Cooking time on clean stoves (minutes/day)	2120	26.1	69.7	1063	43.6	87.8	1057	8.5	37.2
Total number of stoves owned	2120	1.3	0.5	1063	1.4	0.6	1057	1.1	0.3
Total number of fuels used	2120	1.8	0.8	1063	1.4	0.6	1057	2.2	0.8
Reported market price of firewood (Rs./100kg)	2120	522.6	461.7	1063	626.9	580.9	1057	417.7	257.8
Reported market price of LPG (Rs./14.2kg cylinder)	2120	477.3	76.0	1063	452.3	55.5	1057	502.5	85.0
% Spend money on firewood	2019	32%	46%	1024	20%	40%	1057	37%	48%
Panel B: Household demographic and socioeconomic characteristics									
% Hindu	2118	93%	26%	1063	100%	0%	1055	85%	36%
% Scheduled Caste or Tribe	2120	26%	44%	1063	25%	43%	1057	28%	45%
Household Size	2120	5.3	2.4	1063	4.8	2.1	1057	5.7	2.7
% Female headed household	2095	18%	38%	1054	27%	45%	1041	8%	27%
Years of education (head of household)	2082	5.0	4.8	1044	5.8	4.6	1038	4.1	4.9
Years of education (primary cook)	2065	3.7	4.5	1031	4.6	4.5	1034	2.8	4.4
Average monthly expenditures	2051	5,786	5,108	1062	5,654	4,835	989	5,927	5,385
Average hours of electricity	2071	10.0	9.1	1022	17.2	7.1	1049	3.0	4.0
Number of children under 5	2120	0.5	0.8	1063	0.5	0.8	1057	0.5	0.8
% Taken a loan	2120	14%	35%	1063	15%	35%	1057	13%	33%
% SHG membership	2117	13%	33%	1061	15%	36%	1056	11%	31%

Table 2. Probit Regression Results for Clean Stove Ownership and Use

VARIABLES	(1) Owns Clean Stove	(2) Used Clean Stove in Past Week
Relative wealth	0.5***	0.5***
	(0.07)	(0.07)
Average monthly expenditures (log)	0.09	0.1
	(0.07)	(0.07)
# of rooms	0.05**	0.05**
	(0.02)	(0.02)
Years of education (head of household)	0.05***	0.05***
	(0.01)	(0.01)
Age (head of household)	0.009***	0.008**
	(0.003)	(0.003)
Scheduled Caste or Scheduled Tribe	-0.2	-0.3
	(0.1)	(0.2)
Household size	-0.10***	-0.08***
	(0.02)	(0.03)
Number of children under 5	0.2**	0.2**
	(0.06)	(0.06)
Taken a loan	0.01	-0.04
	(0.1)	(0.1)
SHG membership	0.3*	0.3*
	(0.2)	(0.2)
Female only respondent	0.1	0.07
	(0.08)	(0.08)
Female headed household	0.3***	0.4***
	(0.1)	(0.1)
Years of education (primary cook)	0.05***	0.04***
	(0.010)	(0.010)
Hindu	0.2	0.3
	(0.2)	(0.2)
Reported higher than village average price of firewood	0.2*	0.2*
	(0.09)	(0.09)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	-3.4***	-3.2***
	(0.7)	(0.7)
UP (=1 if household lives in UP)	0.7***	0.7***
	(0.2)	(0.2)
Aware of clean stoves	-0.2	-0.2
	(0.1)	(0.1)
Believe clean stoves and fuels can have a medium of better impact on negative effects of traditional stoves	0.3**	0.2
	(0.1)	(0.1)
Toilet	1.2***	1.2***
	(0.2)	(0.2)
Most patient	0.02	-0.02
	(0.10)	(0.09)
Most risk-taking	-0.2**	-0.2**
	(0.09)	(0.09)
Constant	-3.3***	-3.5***
	(0.8)	(0.8)
Observations	1,828	1,826

Robust standard errors, adjusted for clustering of observations at the hamlet level, in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3. Balance Tests for Clean Stove Owners vs. Non-Owners

	Unmatched			Matched		
	Owners	Non-Owners	Normalized Difference	Owners	Non-Owners	Normalized Difference
% Hindu	97%	92%	0.151	97%	98%	-0.0476
% Scheduled Caste or Scheduled Tribe	14%	29%	-0.249	15%	16%	-0.024
Household size	5.1	5.3	-0.041	5.2	5.1	0.026
Age (head of household)	53.6	49.3	0.203	53.8	51.9	0.088
Years of education (head of household)	7.4	4.3	0.419	7.2	6.5	0.098
% Female headed household	25%	16%	0.152	24%	27%	-0.040
Years of education (primary cook)	6.7	3.0	0.495	6.4	5.8	0.094
Hours of electricity	16.0	8.7	0.527	16.1	14.6	0.133
% Owns traditional stove	88%	100%	-0.338	89%	100%	-0.328
Average monthly expenditures	7,222	5,426	0.225	6,835	6,508	0.034
Relative wealth (Range: 1-6)	2.7	1.8	0.585	2.6	2.3	0.231
% BPL	45%	69%	-0.339	45%	58%	-0.180
% Saving possible	14%	5%	0.214	15%	12%	0.046
% Took a loan	12%	15%	-0.063	12%	11%	0.033
% Access to toilet	87%	38%	0.636	86%	78%	0.156
# of cellphones	1.9	1.0	0.398	1.9	1.3	0.236
% Participate in community cleaning	13%	7%	0.155	13%	10%	0.0708
N	380	1446		361	201	

Note: Normalized differences are calculated by taking the difference between the two means and dividing by the square root of the sum of the two standard deviations. Imbens (2014) recommends calculating normalized differences when comparing matched samples. Normalized differences greater than 0.20 are considered large differences.

Table 4. OLS Estimates of the Effect of Improved Stove Use on Key Outcomes

VARIABLES	(1) Biomass fuel	(2) Biomass fuel	(3) Minutes cooking on trad. stoves	(4) Minutes cooking on trad. stoves	(7) Hrs. collecting biomass fuels	(8) Hrs. collecting biomass fuels
Used clean stove in past week	-2.2***	-2.0**	-89***	-72***	-0.5***	-0.5***
	(0.7)	(1.0)	(9.6)	(9.8)	(0.1)	(0.1)
Household size	0.09	-0.3	15***	14***	0.02	-0.07
	(0.7)	(0.7)	(3.8)	(3.8)	(0.06)	(0.06)
Household size squared	0.05	0.08	-0.7**	-0.6**	0.002	0.006
	(0.06)	(0.06)	(0.3)	(0.3)	(0.004)	(0.004)
UP (=1 if household lives in UP)	4.2***	-2.2**	-205***	-129*	0.8***	-1.1***
	(0.8)	(1.1)	(11)	(76)	(0.2)	(0.2)
Female headed household	-1.2	-1.1	23**	27***	-0.2*	-0.1
	(0.8)	(0.9)	(9.2)	(10.0)	(0.1)	(0.1)
Years of education (head of household)	-0.06	-0.001	-0.9	-0.4	-0.01	-0.002
	(0.09)	(0.1)	(0.7)	(0.8)	(0.01)	(0.01)
Years of education (primary cook)	0.1	0.1	-0.6	-0.7	-0.01	-0.02*
	(0.1)	(0.1)	(0.6)	(0.6)	(0.01)	(0.01)
Average monthly expenditures (log)	-1.0*	-0.7	19***	11*	-0.003	-0.04
	(0.6)	(0.5)	(5.6)	(6.1)	(0.08)	(0.08)
Reported higher than village average price of firewood	1.4**	1.3*	6.6	3.1	0.04	0.1
	(0.7)	(0.7)	(6.6)	(7.4)	(0.1)	(0.1)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	-4.2	-1.2	14	-22	1.7**	0.6
	(4.3)	(6.4)	(47)	(59)	(0.7)	(0.9)
Number of children under 5	-0.6	-0.5	8.7**	5.6	-0.1*	-0.07
	(0.4)	(0.4)	(4.0)	(4.2)	(0.06)	(0.06)
Hours of electricity	-0.02	0.004	1.1*	0.3	0.03***	0.02***
	(0.04)	(0.04)	(0.6)	(0.7)	(0.008)	(0.008)
Taken a loan	2.0**	1.9*	1.7	-3.8	0.2	0.1
	(0.9)	(1.0)	(8.7)	(9.4)	(0.1)	(0.1)
SHG membership	-0.3	0.10	28***	35***	0.1	0.08
	(0.7)	(0.7)	(8.1)	(10.0)	(0.2)	(0.2)
Constant	15***	15***	71	122	0.8	2.8***
	(4.6)	(5.1)	(50)	(74)	(0.8)	(0.8)
Observations	1,869	1,869	1,869	1,869	1,869	1,869
R-squared	0.082	0.196	0.472	0.571	0.058	0.259
Hamlet FE	NO	YES	NO	YES	NO	YES

Robust standard errors, adjusted for clustering of observations at the hamlet level, in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5. PSM Estimates of the Effects of Using a Clean Stove			
	(1)	(2)	(3)
VARIABLES	Biomass fuel	Minutes cooking on trad. stoves	Hrs. collecting biomass fuels
Used clean stove in past week	-2.2**	-107***	-0.7***
	(1.0)	(16)	(0.2)
Observations	1,826	1,826	1,826

Clustered bootstrapped standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6. Heckman Two-Step Estimator Results for Clean Stove Use

VARIABLES	(1) Biomass fuel	(2) Minutes cooking on trad. stoves	(3) Hrs. collecting biomass fuels
HH used clean stove in past week	-3.9***	-83***	-0.5*
	(1.2)	(19)	(0.3)
Household size	-0.3	15***	0.005
	(0.8)	(3.9)	(0.06)
Household size squared	0.07	-0.7**	0.003
	(0.07)	(0.3)	(0.004)
UP (=1 if household lives in UP)	4.0***	-206***	0.8***
	(0.8)	(9.3)	(0.1)
Female headed household	-1.5**	23**	-0.3**
	(0.7)	(9.3)	(0.1)
Years of education (head of household)	-0.10	-1.0	-0.01
	(0.08)	(0.7)	(0.01)
Years of education (primary cook)	0.2*	-0.7	-0.010
	(0.1)	(0.8)	(0.01)
Average monthly expenditures (log)	-0.5	18***	0.02
	(0.5)	(5.8)	(0.07)
Reported higher than village average price of firewood	1.2**	5.6	-0.00007
	(0.5)	(5.5)	(0.09)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	-3.0	19	2.1***
	(4.7)	(40)	(0.7)
Number of children under 5	-0.4	8.7**	-0.10
	(0.4)	(3.8)	(0.06)
Hours of electricity	-0.002	1.0*	0.03***
	(0.04)	(0.6)	(0.007)
Taken a loan	1.8**	2.5	0.2
	(0.9)	(8.6)	(0.1)
SHG membership	0.06	30***	0.2
	(0.7)	(8.3)	(0.1)
Lambda	1.1	-6.3	-0.01
	(0.9)	(12)	(0.2)
Rho	0.09	-0.05	-0.007
Constant	12***	76	0.4
	(3.8)	(47)	(0.6)
Observations	1782	1782	1782

Standard errors, calculated with the jackknife method, in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 7. OLS Results for Fuel Measurement Survey

VARIABLES	(1) Biomass fuel	(2) Biomass fuel	(1) Minutes cooking on trad. stoves	(2) Minutes cooking on trad. stoves
Used clean stove during monitoring period	-3.8***	-2.7***	-113***	-98***
	(0.6)	(0.5)	(12)	(14)
Household size	-0.1	-0.2	1.8	1.0
	(0.2)	(0.2)	(2.9)	(2.4)
Household size squared	0.02	0.02	-0.03	-0.003
	(0.01)	(0.01)	(0.2)	(0.1)
UP (=1 if household lives in UP)	-2.5***	-3.4***	-102***	159***
	(0.7)	(0.9)	(17)	(18)
Female headed household	-0.6*	-0.4	-9.6	-7.4
	(0.4)	(0.4)	(7.6)	(7.7)
Years of education (head of household)	-0.04	-0.04	-0.5	-0.4
	(0.04)	(0.04)	(0.6)	(0.6)
Years of education (primary cook)	-0.0006	-0.03	-0.5	-0.6
	(0.03)	(0.04)	(0.6)	(0.5)
Average monthly expenditures (log)	0.2	0.2	-3.1	-2.8
	(0.2)	(0.2)	(3.8)	(3.9)
Reported higher than village average price of firewood	0.4	0.4	2.6	6.6
	(0.3)	(0.3)	(5.6)	(5.7)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	1.6	-0.7	54*	6.3
	(2.0)	(1.9)	(32)	(37)
Number of children under 5	0.02	-0.07	3.5	-0.3
	(0.2)	(0.2)	(3.2)	(3.1)
Hours of electricity	-0.05*	-0.02	0.5	0.6
	(0.03)	(0.03)	(0.5)	(0.5)
Taken a loan	-0.01	-0.2	-0.9	-6.9
	(0.3)	(0.4)	(7.0)	(7.0)
SHG membership	-0.6	-0.6	14	1.2
	(0.4)	(0.5)	(8.8)	(12)
Number of household members cooked for	0.6***	0.6***	6.6***	7.3***
	(0.09)	(0.09)	(1.2)	(1.1)
Breakfast (=1 if breakfast was cooked)	0.1	0.9	-8.3	23
	(0.5)	(0.7)	(12)	(17)
Morning tea (=1 if morning tea was cooked)	0.06	0.1	16**	2.3
	(0.4)	(0.4)	(7.5)	(6.2)
Lunch (=1 if lunch was cooked)	1.2**	0.7	46***	24**
	(0.5)	(0.6)	(10)	(11)
Afternoon tea (=1 if afternoon tea was cooked)	0.2	0.8*	-27***	-3.5
	(0.5)	(0.5)	(8.3)	(7.2)
Dinner (=1 if dinner was cooked)	0.8	1.1	17	28*
	(0.7)	(0.8)	(15)	(15)
Food only (=1 if only food was prepared)	-1.2**	-0.07	-35***	-3.1
	(0.5)	(0.5)	(12)	(12)
Constant	5.0**	5.0**	207***	32
	(2.1)	(2.4)	(39)	(45)
Observations	1,047	1,047	1,047	1,047
R-squared	0.231	0.463	0.355	0.622
Hamlet FE	NO	YES	NO	YES

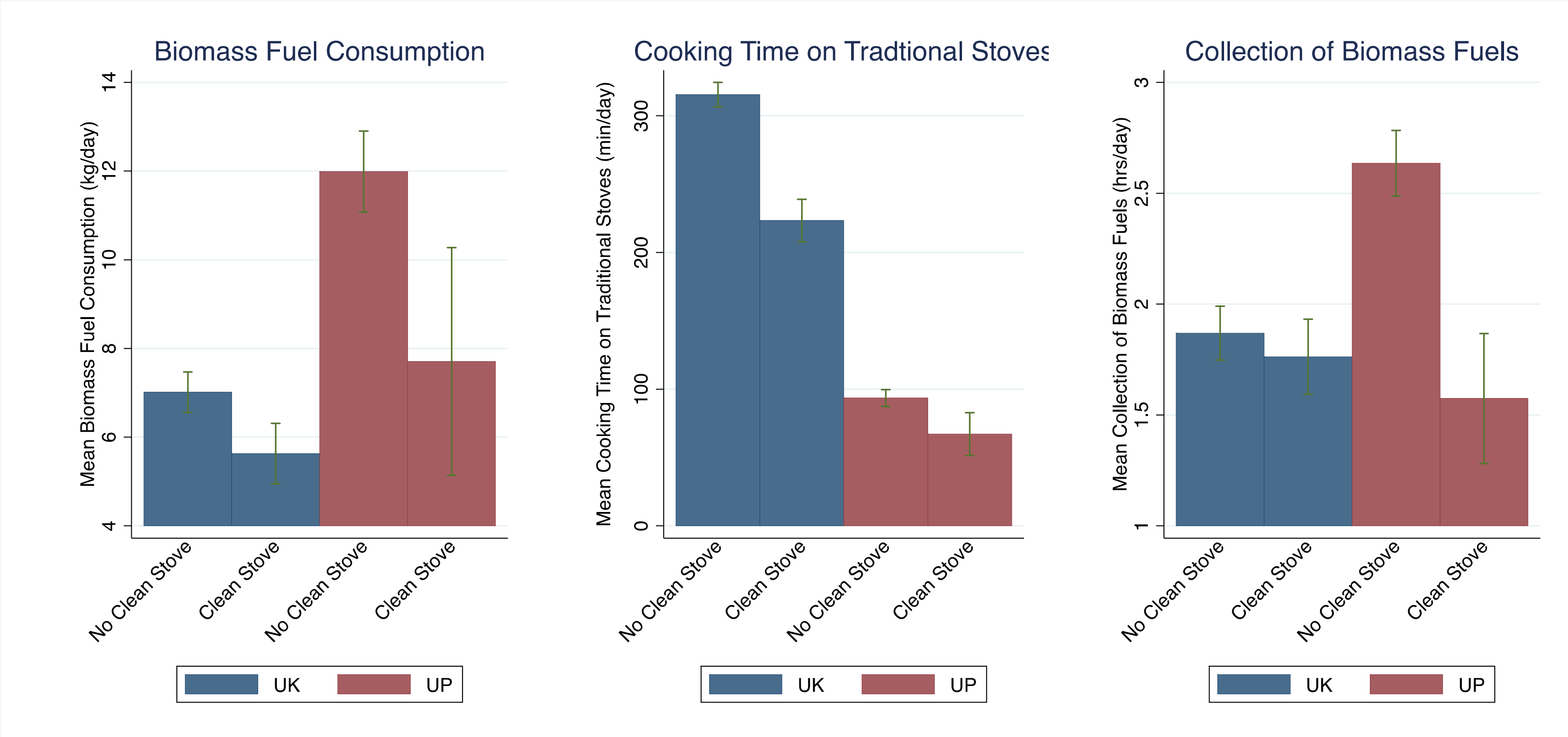
Robust standard errors, adjusted for clustering of observations at the hamlet level, in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A1. OLS Estimates of the Effect of Clean Stove Use on Key Outcomes by State

	Biomass fuel				Minutes cooking on trad. stoves				Hrs. collecting biomass fuels			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	UK	UP	UK	UP	UK	UP	UK	UP	UK	UP	UK	UP
Used clean stove in past week	-1.5***	-4.1*	-1.1**	-4.1	-103***	-39***	-87***	-41***	-0.2	-1.2***	-0.2**	-1.0***
	(0.4)	(2.3)	(0.5)	(2.8)	(11)	(12)	(13)	(13)	(0.1)	(0.2)	(0.1)	(0.3)
Household size	1.0***	-0.3	0.8***	-1.1	38***	-3.9	36***	-3.0	0.2**	-0.2*	0.1*	-0.3**
	(0.3)	(1.0)	(0.3)	(1.0)	(7.4)	(4.8)	(7.6)	(4.7)	(0.09)	(0.09)	(0.07)	(0.10)
Household size squared	-0.03	0.08	-0.010	0.1	-2.2***	0.4	-1.9**	0.3	-0.005	0.01**	-0.004	0.02***
	(0.02)	(0.07)	(0.02)	(0.08)	(0.7)	(0.3)	(0.8)	(0.3)	(0.007)	(0.005)	(0.006)	(0.006)
Female headed household	-0.7	-1.4	-0.7	-1.8	31**	-0.6	36***	-6.4	-0.1	-0.6**	0.04	-0.5*
	(0.6)	(2.0)	(0.6)	(2.1)	(12)	(11)	(14)	(11)	(0.1)	(0.3)	(0.1)	(0.3)
Years of education (head of household)	0.02	-0.10	0.02	0.005	-0.9	-1.1	-0.6	-0.3	-0.03**	0.02	-0.006	0.01
	(0.06)	(0.2)	(0.06)	(0.2)	(1.1)	(0.8)	(1.3)	(0.8)	(0.01)	(0.02)	(0.01)	(0.02)
Years of education (primary cook)	-0.006	0.3	-0.04	0.3	-1.7*	0.2	-2.4**	1.1	0.01	-0.03	-0.001	-0.03
	(0.05)	(0.2)	(0.06)	(0.2)	(0.9)	(0.7)	(1.0)	(0.8)	(0.01)	(0.02)	(0.01)	(0.02)
Average monthly expenditures (log)	-0.4	-1.8	-0.7	-0.5	12	25***	5.1	18**	0.05	-0.2	0.002	-0.1
	(0.5)	(1.4)	(0.5)	(1.1)	(7.4)	(6.8)	(8.2)	(7.9)	(0.09)	(0.2)	(0.08)	(0.2)
Reported higher than village average price of firewood	1.3**	1.6	1.6**	1.1	0.5	14*	6.6	4.0	0.01	0.06	0.1	0.2
	(0.6)	(1.2)	(0.7)	(1.3)	(10)	(8.4)	(11)	(9.0)	(0.1)	(0.2)	(0.1)	(0.2)
Reported market price of LPG (1000 Rs./14.2kg cylinder)	-11***	-2.5	-11*	2.0	204*	-0.3	79	-24	5.2***	0.2	1.5	0.07
	(4.2)	(5.9)	(6.3)	(9.5)	(106)	(48)	(141)	(58)	(1.1)	(0.9)	(1.2)	(1.2)
Number of children under 5	-0.3	-0.6	-0.4	-0.4	7.6	6.9	5.1	4.7	-0.1	-0.1	-0.08	-0.1
	(0.3)	(0.6)	(0.3)	(0.7)	(7.1)	(4.9)	(7.5)	(4.8)	(0.08)	(0.09)	(0.07)	(0.1)
Hours of electricity	-0.03	0.03	-0.008	-0.05	1.7**	-2.2***	0.5	-1.9**	0.03***	0.02	0.02***	0.02
	(0.03)	(0.1)	(0.04)	(0.1)	(0.8)	(0.8)	(0.8)	(0.9)	(0.008)	(0.02)	(0.008)	(0.03)
Taken a loan	1.7**	2.3	1.1	2.7	16	-13	9.0	-18	0.6***	-0.08	0.4**	-0.1
	(0.7)	(1.7)	(0.7)	(2.0)	(13)	(11)	(13)	(12)	(0.2)	(0.2)	(0.2)	(0.2)
SHG membership	-0.1	-0.7	0.7	-1.2	29**	30***	38**	25**	0.08	0.3	0.02	0.1
	(0.6)	(1.4)	(0.6)	(1.4)	(13)	(8.3)	(15)	(11)	(0.2)	(0.2)	(0.1)	(0.3)
Constant	12***	26**	14***	16	-25	-106*	106	-36	-2.1**	4.9***	0.3	4.6***
	(3.6)	(11)	(4.0)	(11)	(80)	(57)	(101)	(65)	(0.9)	(1.4)	(0.9)	(1.6)
Observations	948	921	948	921	948	921	948	921	948	921	948	921
R-squared	0.086	0.036	0.195	0.160	0.218	0.067	0.344	0.267	0.100	0.047	0.399	0.177
Hamlet FE	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES

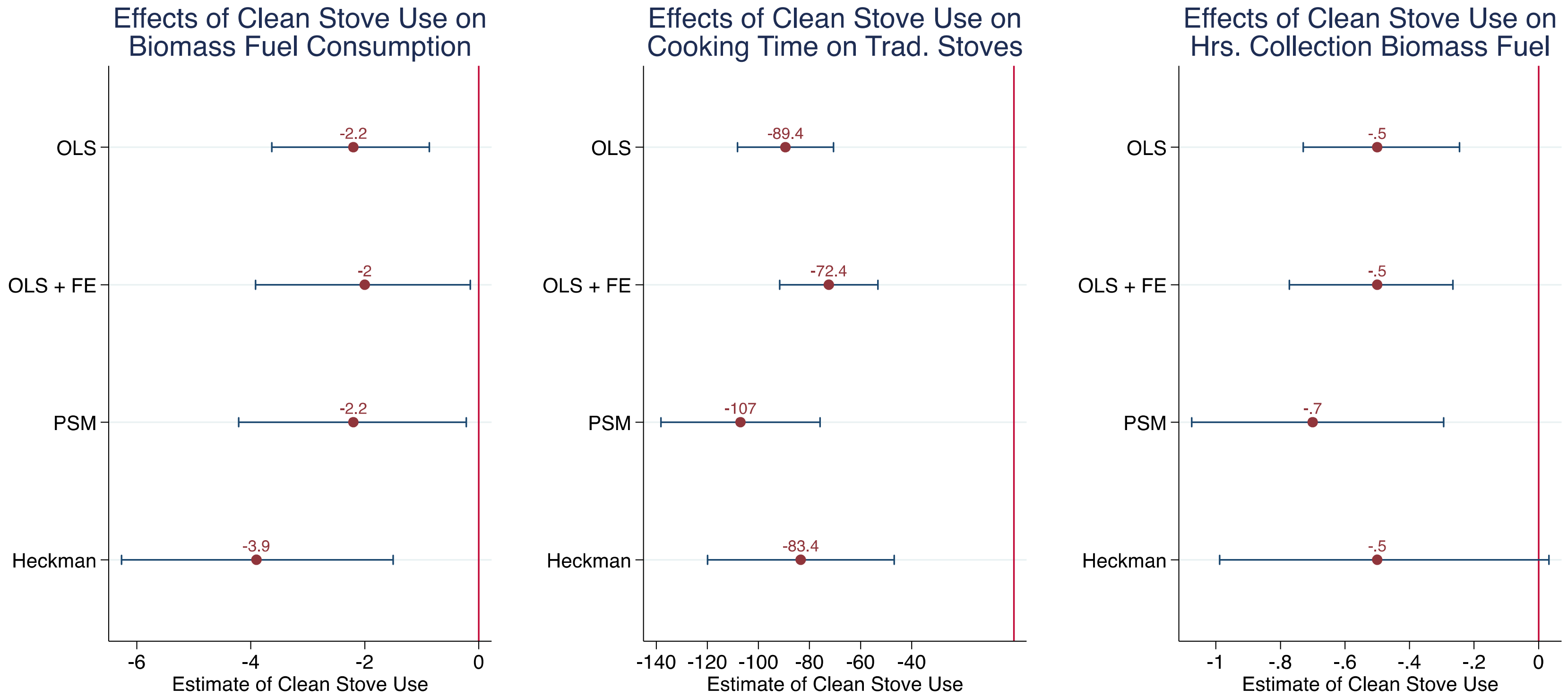
Robust standard errors, adjusted for clustering of observations at the hamlet level, in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Figure 1. Key outcomes broken out by clean stove ownership and state



Note: Means for each group are presented with green bars representing 95% confidence intervals around the mean.

Figure 2. Regression coefficient plots for clean stove use



Note: Regression coefficients on clean stove use from each of the models are presented. The blue bars represent 95% confidence intervals.